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Assessment of nitrogen reduction by constructed wetland based on InVEST: A case study of the Jiulong River Watershed, China

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ABSTRACT

The Jiulong River watershed (JRW) in southeast China includes livestock breeding and agriculture, leading to large amounts of non-point source pollution. Nitrogen (N) reductions were simulated and mapped using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) under scenarios that were built considered both constructed wetlands (CWs) and climate change, which are not common in the literature on ecosystem services assessments. The results showed that the amount of N exported from non-point sources within the JRW was 12,569 $t{\cdot}yr^{-1}$. The areal N load was relatively higher in the north, while more N exported in the southeast. Constructed riparian wetlands can intercept and reduce the N loads that enter water bodies, but climate change may be a factor driving the deterioration of water quality. The methodology can be generalized to reduce other contaminants, and provides a tool for decision-makers to weigh the costs and benefits of urbanization and conservation.

1. Introduction

Ecosystems provide a variety of essential ecological functions to support life and supply benefits to humanity, and these functions are also called as ecosystem services (ES) (Groot et al., 2010; MA, 2005). Water purification is a significant ecosystem function that is directly related to the aquatic environment and life, as well as those of human beings (Keeler et al., 2012). In addition, the ocean is also affected by terrestrial nutrients. As the channels connecting land and oceans, rivers play vital roles in the transport of terrigenous material to the marine environment. Approximately 2.25×10^{10} $t{\cdot}yr^{-1}$ of terrestrial materials enter the ocean on a global scale (Wu et al., 2017). In recent years, there has been a significant increase in social-economic development. To increase crop production and meet the increasing demands of the growing population, fertilizer application and poultry/livestock culture have also increased (Cao et al., 2014; Strokal et al., 2014). In regard to environmental and water quality management on land, non-point source pollution is an important problem, which occurs when precipitation, snowmelt, or irrigation water runs over or below the ground. Surface and subsurface flow can pick up pollutants and introduce them into rivers, groundwater, and eventually coastal waters (Liu et al., 2008). Due to the characteristics of randomness, intermittence, latency, lag and sophistication (Hong et al., 2008), it is of great importance to study non-point source pollution.

One way to reduce non-point source pollution is to reduce the number of anthropogenic inputs, such as those from fertilizer application. Another way is to utilize the natural purification services provided by ecosystems, which include retaining or degrading pollutants before they enter water bodies. For example, vegetation can absorb or transform some pollutants; soils can filter flows and trap some soluble pollutants (Sharp et al., 2016); riparian vegetation plays an especially important role, which often serves as the last barrier before pollutants enter a stream (Mayer et al., 2007a; X. Zhang et al., 2009).

Land use and land cover (LULC) and climate change should be the primary factors used to assess ES, especially water-related ES (Bateman et al., 2013). LULC varies with time and space, leading to changes in the amounts and locations of ES (Bennett et al., 2009; Lautenbach et al., 2011) and resulting in the heterogeneity of ES. Green infrastructure has become a prominent concept in recent years (Ahern, 2007; Mell, 2008; Spanò et al., 2017), which is considered to consist of natural, semi-natural and artificial networks of multifunctional ecological systems within, around and between urban areas at all spatial scales (Tzoulas et al., 2007). Green space has significance in a wide variety of ES, from environmental quality improvement to climate change adaptation and

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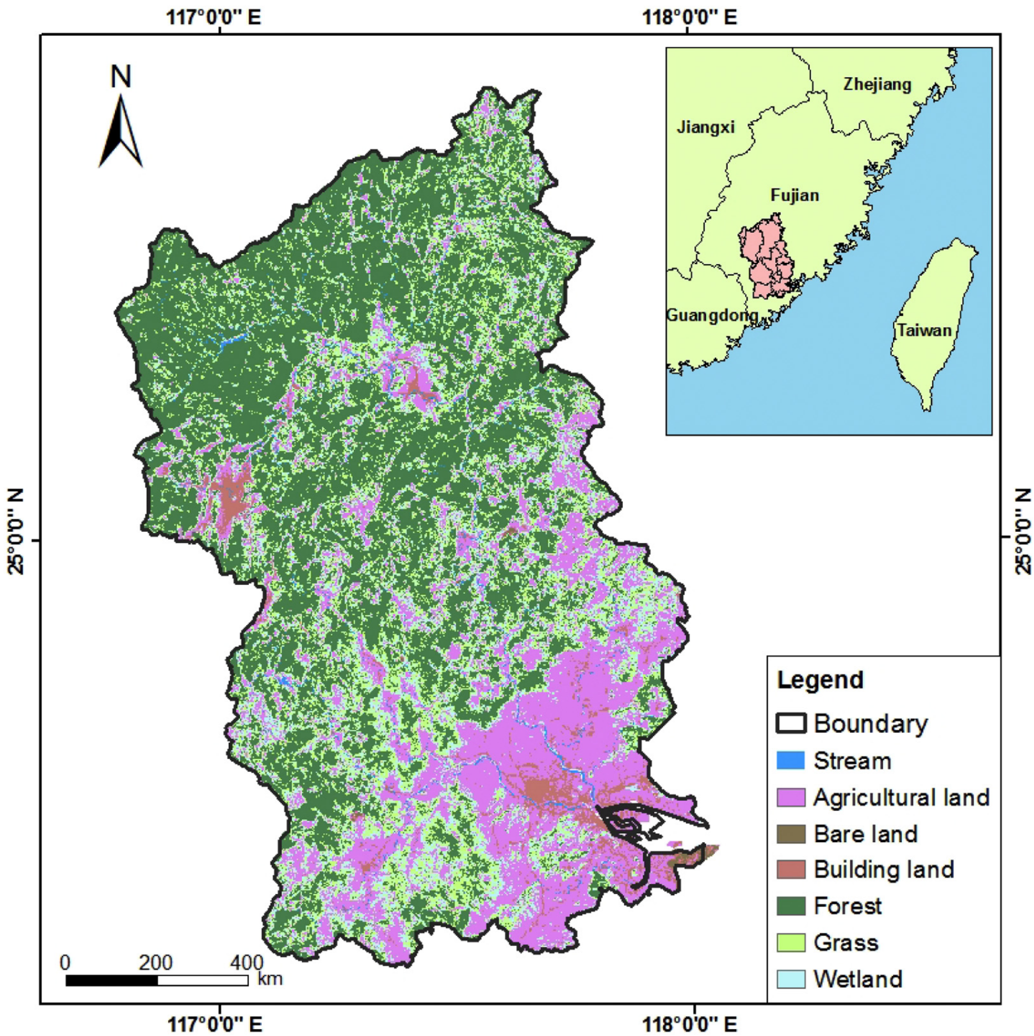

Fig. 1. Study area.

Table 1
The sources of data used in this study.

Data	Descriptions	Sources
LULC (land use/land cover)	A spatially continuous GIS raster dataset for 2002 with a resolution of 30 m. The LULC code for each pixel is an integer.	Produced by the interpretation of 30-m Landsat thematic mapper (TM) data.
DEM (digital elevation model)	A 30 m-resolution GIS raster dataset with an elevation value for each cell.	Geospatial Data Cloud, Chinese Academy of Sciences, http://www.gscloud.cn/
Pre (precipitation)	A 30 m-resolution GIS raster dataset for the current (1970–2000) and future (2041–2060) periods with an annual average precipitation for each pixel.	Worldclim-Global Climate Date, http://worldclim.org/
Biophysical table	A .csv table of LULC classes, containing the data on water quality coefficients used in this tool, including N loading, retention efficiency, and proportion of dissolved N.	(Berg et al., 2016; Han et al., 2016; Huang et al., 2004; Pan, 2016; Sharp et al., 2016; Ying et al., 2016)

mitigation (Ely and Pitman, 2012; Pakzad and Osmond, 2016), and provides social and economic benefits for human-beings, such as improving psychological health levels and mental well-being, promoting local economic activities and increasing property values (ARUP, 2014; UEPA, 2014). As an important branch of green infrastructure, constructed wetlands (CWs) are systems that are designed and constructed to utilize the natural processes to assist in treating wastewater, including wetland vegetation, soils and associated microbial assemblages (Vymazal, 2007). In addition, the purified water produced in constructed wetlands is also suitable for reuse (Lee et al., 2009). Compared to conventional treatment systems, CWs are low cost, easy to operate and maintain (Kivaisi, 2001) and have relatively high nitrogen (N) removal efficiencies (Lee et al., 2009; Vymazal, 2007, 2010). Based on the type of macrophytic growth and water flow regime, CWs can be classified into many types (Vymazal and Kröpfelová, 2008), but generally speaking, free water surface (FWS) systems, horizontal subsurface flow (HSSF) and vertical subsurface flow (VSSF) systems are the most commonly designed and used types in China (D. Zhang et al., 2009). With regard to climate change, scientists and policy-makers have reached a consensus that some human-induced climate change is unavoidable (Whitehead et al., 2009). The quantity and movement of water through the landscape can shift with climate change, which will also lead to the alteration of nutrient transport dynamics.

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) was developed by the Natural Capital Project (NatCap, www.naturalcapitalproject.org) and is a spatially explicit ES modeling tool

Table 2
Historical status of N load and export in the JRW at the county scale.

Name	Area (ha)	Load		Export	
		Total ($t \cdot yr^{-1}$)	Areal rate ($kg \cdot ha^{-1}$)	Total ($t \cdot yr^{-1}$)	Areal rate ($kg \cdot ha^{-1}$)
Zhangping	298,013	4130	13.86	2637	8.85
Longyan	251,067	3430	13.66	2243	8.93
Yongchun	3390	47	14.00	27	7.88
Shanghang	13,163	197	14.97	121	9.19
Huaan	131,115	1695	12.93	1167	8.90
Nanjing	192,762	2424	12.57	1726	8.96
Changtai	89,998	936	10.40	825	9.17
Zhangzhou	27,674	243	8.80	261	9.45
Tongan	3132	30	9.48	25	7.93
Yongan	16,602	245	14.76	141	8.48
Datian	35,804	482	13.47	297	8.28
Liancheng	36,597	552	15.08	334	9.13
Anxi	103,342	1262	12.21	923	8.93
Yongding	2235	32	14.51	2	0.82
Pinghe	111,749	1320	11.81	966	8.65
Yunxiao	63	1	10.96	0	6.80
Longhai	110,594	976	8.82	621	5.61
Zhangpu	29,499	304	10.31	250	8.46
Haicang	2917	23	7.89	2	0.80
Total	1,459,717	18,329	12.56	12,569	8.61

that comprises a series of modules (Lin et al., 2017; Sharps et al., 2017). The InVEST model estimates, quantifies and maps the ES provided by terrestrial, freshwater and marine systems using LULC patterns and climate conditions (Sharp et al., 2016). By varying land use management and analyzing the output from InVEST, information can be provided to policy-makers weighing the tradeoffs in ES, biodiversity conservation and other land use objectives (Polasky et al., 2011).

The objectives of this study are to (1) quantify the historical status of N export from non-point sources in JRW with a spatially explicit map; (2) build scenarios with CWs and map the non-point source N exported from JRW under different LULC and climate change scenarios; and (3) propose non-point source N reduction strategies for management.

2. Methods

2.1. Study area

The Jiulong River watershed (JRW) in southeastern China serves as our study area (Fig. 1). As the second largest river in Fujian Province, the Jiulong River has three tributaries, the Beixi River, Xixi River and Nanxi River. The entire river watershed drains more than 14,000 km^2, mainly including 3 city-level administrative units of Longyan, Zhangzhou and Xiamen Municipality, and discharges approximately 14 billion $m^3 \cdot yr^{-1}$ of water into Xiamen Bay. The JRW is one of the most developed areas in Fujian Province and includes livestock breeding and agriculture, making it the major contributor of nutrients to Xiamen Bay. At the same time, the JRW is a significant source of water for drinking, irrigation and industrial use.

2.2. Data collection and processing

Spatial and biophysical data were used in this study; they are LULC, DEM (digital elevation model), precipitation and biophysical table data. The sources of these data are shown in Table 1. The raster datasets, i.e., LULC, DEM and precipitation, were manipulated and processed in ArcGIS 10.2 software (ESRI) to guarantee the consistency of the coordinate system and projection, and the spatial resolution is 30 m. In addition, the DEM was corrected and filled to remove sinks. The future climate data were acquired from the Beijing Climate Center Climate System Model version 1.1 (BCC_CSM1.1) from Climate Model Intercomparison Project five (CMIP5), which has conducted most of the CMIP5 experiments (Xin et al., 2012) and has exhibited relatively good performance of climate simulations in the East-Asian monsoon zone (Guo et al., 2008). The datasets were chosen for three representative concentration pathways (RCPs), e.g., RCP 26, RCP 45, and RCP 86, to provide a low, medium and high range of potential climate paths for the study area. The biophysical table contains the data on the water quality coefficients, such as the N loading for each land use type, the maximum retention efficiency for each land use type, and the proportion of dissolved N over the total amount of N, and the coefficients are obtained from the published literature.

2.3. Model description

The nutrient delivery ratio (NDR) module of InVEST (version 3.3.3) was used to map the N sources from the watersheds and their transport to the stream. The NDR module uses a mass balance approach that describes the movement of nutrient masses (mainly nitrogen and phosphorus) through space. It represents the long-term, steady-state flow of nutrients through empirical relationships rather than the details of the nutrient cycle.

The module computes the N export from a watershed based on the pixel level in two steps. First, each pixel is characterized by its N load and N delivery ratio. For each pixel, the N load can be divided into sediment-bound and dissolved N portions:

$$load_{sur,i} = (1 - proportionsubsurface_i) \bullet load_i \tag{1}$$

$$load_{subs,i} = proportionsubsurface_i \bullet load_i \tag{2}$$

where $load_i$ is the modified load in pixel i and $proportion\_subsurface_i$ is the proportion of dissolved N over the total amount of N, which is expressed as a ratio between 0 and 1. The NDR is a function of the upslope area and the retention efficiencies of the LULC types on the downslope flow path. For each pixel, the surface NDR is defined as:

$$NDR_{sur,i} = NDR_{0,i}\left(1 + \exp\left(\frac{IC_i - IC_0}{k}\right)\right)^{-1} \tag{3}$$

$$NDR_{0,i} = 1 - \begin{Bmatrix} eff_{LULC_i} \cdot (1 - s_i), & \text{if } down_i \text{ is a stream pixel} \\ eff'_{down_i} \cdot s_i + eff_{LULC_i} \cdot (1 - s_i), & \text{if } eff_{LULC_i} > eff'_{down_i} \\ eff'_{down_i}, & \text{otherwise} \end{Bmatrix} \tag{4}$$

$$s_i = \exp\left(\frac{-5 \bullet l_i}{l_{LULC_i}}\right) \tag{5}$$

where $NDR_{0,\ i}$ is the proportion of N that is not retained by the downstream pixels, IC_i is a topographic index, IC_0 and k are calibration parameters, eff_{LULC_i} is the maximum retention efficiency that LULC type i can reach, and $eff_{down_i}{}'$ is the effective downstream retention on the pixel directly downstream from i. s_i is a step factor, where l_i is the distance from pixel i to its downstream neighbor, and l_{LULC_i} is the N retention length of the landcover type on pixel i. The subsurface NDR is defined as:

$$NDR_{susb,i} = 1 - eff_{subs}\left(1 - \exp\left(\frac{-5 \bullet l_i}{l_{subs}}\right)\right) \tag{6}$$

where eff_{subs} is the maximum N retention efficiency that can be reached through subsurface flow, l_i is the distance from the pixel to the stream, and l_{subs} is the subsurface flow retention length.

The second step is that, at the watershed/subwatershed outlets, the module sums the pixel-level N exports as the total N export at the watershed level:

$$x_{exp_{tot}} = \sum_i (load_{sur,i} \bullet NDR_{sur,i} + load_{subs,i} \bullet NDR_{subs,i}) \tag{7}$$

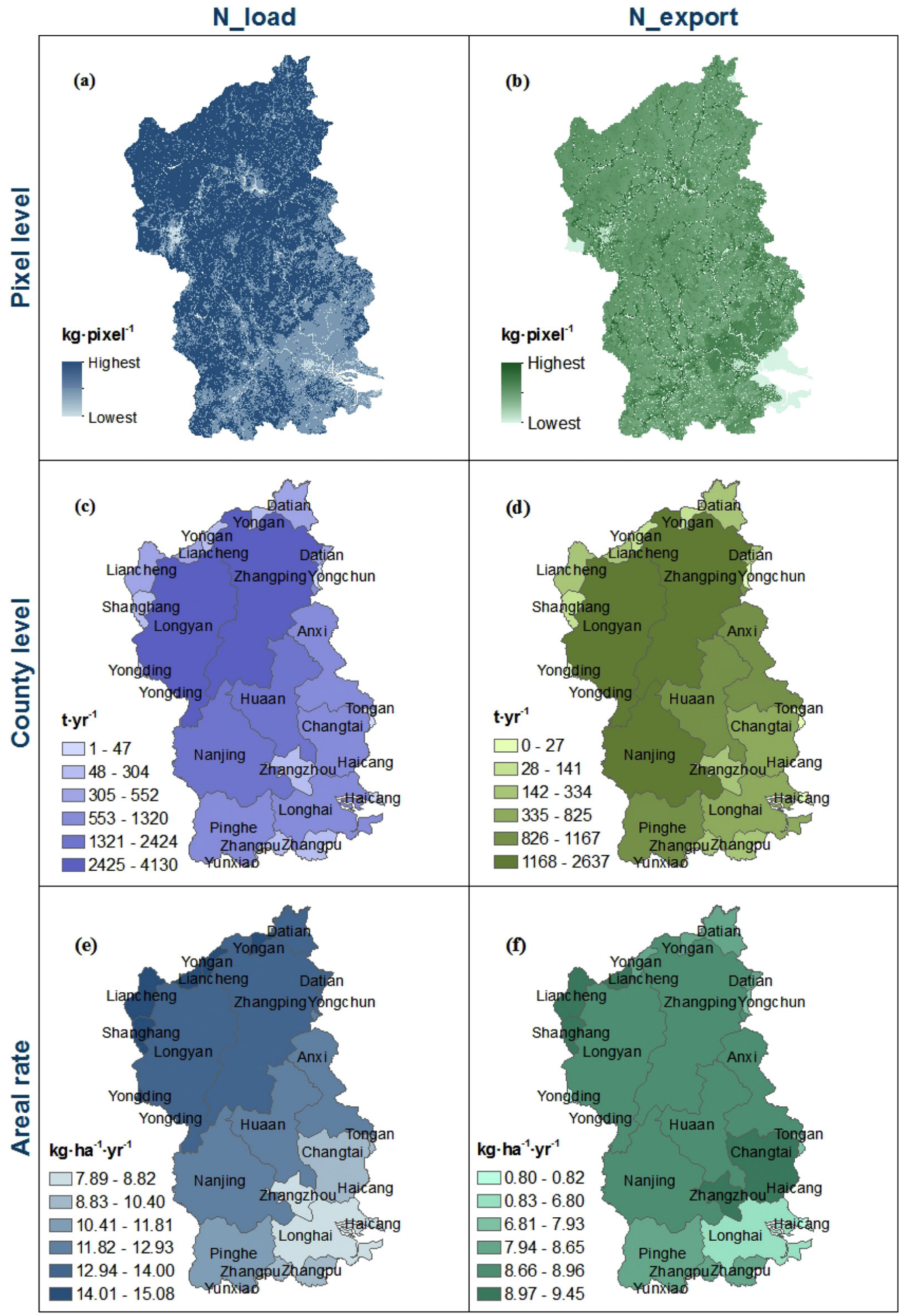

Fig. 2. Historical status of N load and export in the JRW.

2.4. LULC scenario building

Scenario analysis helps managers foresee possible trends, which avoids losses from incorrect strategies. There are many methods to build scenarios (Berg et al., 2015), and some studies have built scenarios by changing the values of the input data, such as by exchanging the precipitation or LULC data among different groups (Bai et al., 2016). Additionally, models have been used to forecast future LULC patterns, such the CLUE-S (the conversion of land use and its effects at small regional extent) (Pan, 2016) and IDRISI Land Change Modeler (Rosenthal et al., 2015). To make InVEST more user-friendly, NatCap developed a standalone tool to create the LULC patterns for different scenarios, named the “scenario generator tool”. This tool provides a relatively simple method to generate scenarios based on the land suitability principle. The tool outputs maps that depict future LULC patterns by combining inputs of transition likelihood with physical factors that determine suitability (Sharp et al., 2016). The LULC scenario maps in this study were created with the scenario generator tool and ArcGIS

Table 3
Areas of LULC categories in alternative LULC scenarios (km^2).

Category	Historic	S1	S2	S3
Forest	9012	9012	9012	9012
Grass	458	448	454	444
Wetland	34	34	34	34
Agricultural land	4645	4609	4554	4518
Building land	283	356	283	356
Bare land	27	/	27	/
Constructed wetland	/	/	95	94

Table 4
Impacts on N load and export from LULC and climate changes.

Scenarios		Load increment		Export increment	
Climate change	LULC	Total ($t·yr^{-1}$)	Areal rate ($kg·ha^{-1}$)	Total ($t·yr^{-1}$)	Areal rate ($kg·ha^{-1}$)
Historic pre	S1	−34.29	−0.02	−27.21	−0.02
	S2	15.25	0.01	−71.05	−0.05
	S3	−19.25	−0.01	−97.74	−0.07
RCP 26	Current LULC	0.00	0.00	0.73	0.00
RCP 45		0.00	0.00	−0.07	0.00
RCP 85		0.00	0.00	0.03	0.00

10.2. In this study, three alternative LULC scenarios were developed to examine the potential effects of CWs on N export reduction; they are

S1: Policy-based scenario: Based on the *Plan for Land Utilization of Fujian Province (2006–2020)*, the area of building land increased by 26% in this scenario, while the areas of agricultural and bare lands decreased.
S2: Managed scenario: A 50-meter-buffer zone was established on both sides of the stream in this scenario. All lands expect for forest, wetlands and building lands within the buffer were converted into CWs.
S3: Integrated scenario: This scenario was the combination of S1 and S2. In this scenario, both policy and CWs were taken into account to simulate the future LULC with the construction of CWs.

2.5. Scenarios simulation

Non-point source N exports under different scenarios were simulated by using the NDR module at the county scale, based on the LULC and climate change scenarios. To assess the effect of N reduction under different scenarios, the changes in N export were determined and mapped as a LULC-dependent variable that quantified the effect of green infrastructure on N reduction. A change in each scenario relative to its current state can be calculated as (modified from Leh et al. (2013)):

$$NECI_i = \left(\frac{NE_{S_i} - NE_C}{NE_C}\right) \times 100\% \tag{8}$$

where $NECI_i$ is the N export change index under scenario i, and NE_{S_i} and NE_C are the N export under scenario i and the current status, respectively.

2.6. Model calibration

Observed N export data from the watershed were used to calibrate and validate the results of the NDR module. It should be noted that the total N ($mg·L^{-1}$) observation data could not be directly compared with the model outputs ($kg·yr^{-1}$) due to the different units. To compare the observed data with the model outputs, the units of the concentration values were converted into annual loads. As the InVEST tool cannot account for N inputs from point sources, such as domestic sewage and industrial wastewater, an additional value was added to the total annual N export of the watershed. Point-source N emissions were estimated based on the amounts of domestic sewage and industrial wastewater and the N concentrations of them (Wang et al., 2006). To calibrate the model, the parameters should be adjusted until the model validation passed with good quality.

3. Results and discussions

3.1. Model validation

The empirical observations from Chen et al. (2008) were used to calibrate and validate the NDR module. By adjusting the parameters of the NDR module, the total N export from non-point sources within the JRW was 12,569 $t·yr^{-1}$ (Table 2). As a result, the total N export was 25,359 $t·yr^{-1}$ with the addition of point source pollution, while the observed data were 26,138 $t·yr^{-1}$. The results indicated that the percent differences between the modeling and observed data were 2.98%, which indicated that the model exhibited good performance.

3.2. Historical status of N load and export in the JRW

The pixel-level maps show the total N loads and how much of the load from each pixel eventually reaches the stream (Fig. 2a and b). The N load was relatively higher in the northern area, while higher N export occurred in the southeastern area, indicating that the N retention efficiency differed among different LULC types (Beaulac and Reckhow, 1982; Lin, 2004). Attention was drawn to the area covered by the lightest color, which indicated that N was not entering the river. The amount of N that reaches the stream depends on spatial factors, such as flow direction (derived from the DEM dataset) and precipitation, and some of the biophysical coefficients (Sharp et al., 2016). Thus, these areas demonstrate that most of the N input within these areas enters the coastal bay–river system. In actuality, Chen et al. (2013) proved that more than one-quarter of the total N load that entered Xiamen Bay was attributed to terrestrial activities.

Watershed management usually occurs in the administrative district units, so the N load and export were simulated at the county scale (Fig. 2c–f). The N load was higher in the northwestern part of the JRW than in the southeast, and this was also the case for the N export. Higher N export occurred in the northern and western areas of the JRW, namely Zhangping, Longyan and Nanjing Counties (Fig. 2c and d), due to the large areas. Overall, on an annual basis, the mean N load in the JRW was 12.56 $kg·ha^{-1}·yr^{-1}$, and the mean export was 8.61 $kg·ha^{-1}·yr^{-1}$ (Fig. 2e and f). Zhangzhou City showed the highest areal N export rate (9.45 $kg·ha^{-1}$) (Fig. 2f), instead of the northwestern counties. This result likely occurred because even though the loads over these counties were higher, the lands there are mostly covered by forest, which exhibit high N retention and reduction efficiencies and the N was exported from the area. The main land use type in the southeastern portion of the JRW was agricultural land, which has high N loads and low retention efficiency.

3.3. LULC scenarios

The current and three alternative LULC scenarios are shown in Table 3. Overall, the LULC shifted modestly toward building land from the other types. The forest areas were the greatest in each scenario, accounting for more than 60% of the land cover in the JRW, while the wetland areas were relatively small. The bare land was ideally converted into other LULC types in S1 and S3, and agricultural land shrank at different extents.

3.4. Spatial changes of N export under different scenarios

In general, the impacts from LULC and climate changes were

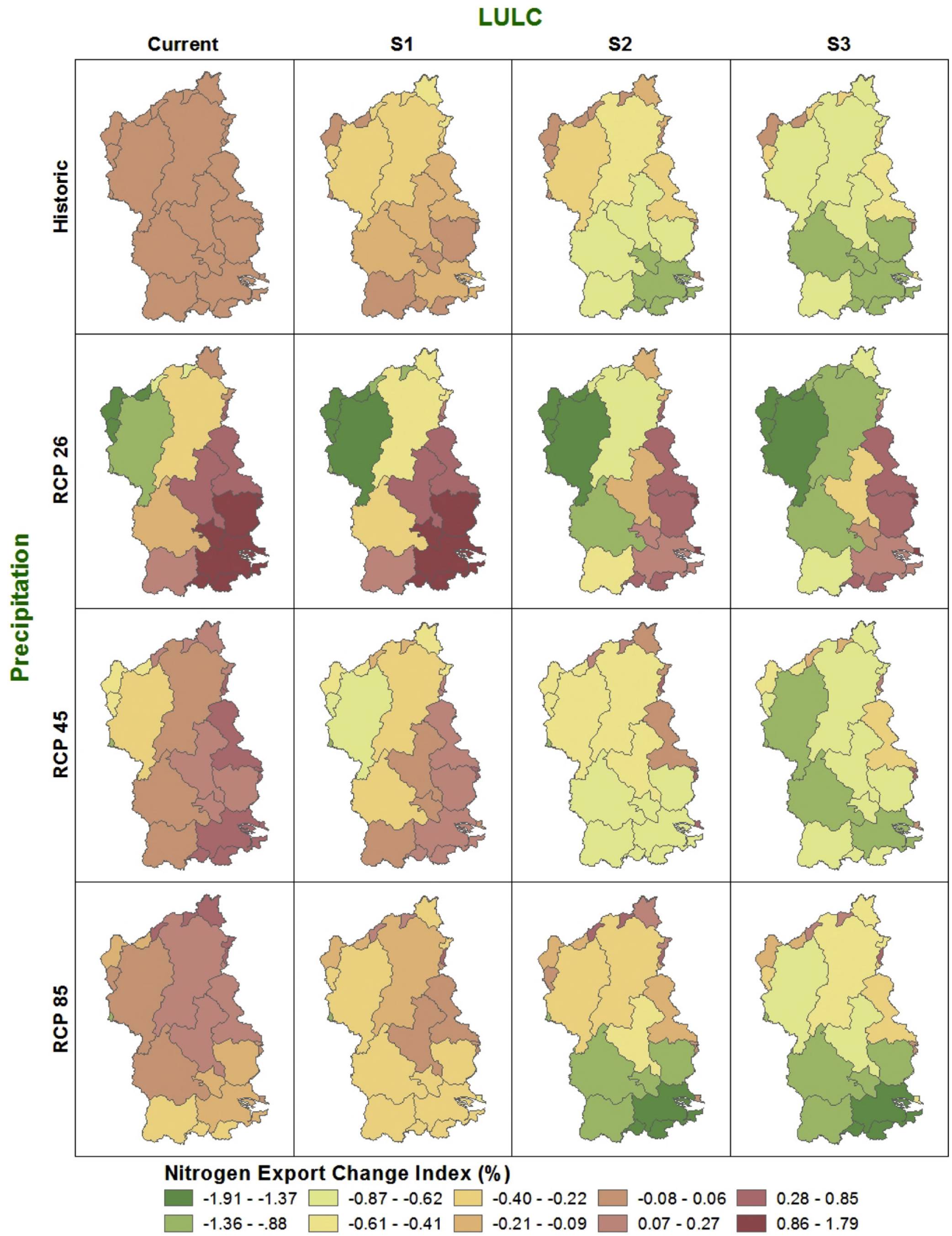

Fig. 3. NECI under different scenarios in the JRW.

simulated based on the basic condition, i.e., current LULC + historic pre (Table 4). The results indicated that the LULC changes could affect both the N load and export, while climate change had little influence on N load and resulted in slight changes in N export. Fig. 3, which depicts the NECI from the baseline to future scenarios, supported the theory that the changes in N export were driven by land cover changes. In general, with the protection of forest, the export of N reduced under each scenario at different degrees, up to 1.91% compared to the current status. Most of this is attributed to the change from agricultural land to building land, which has a reduction effect. In terms of S1, the transition to building land occurred mostly from agricultural land in the north and from bare land in the southeast, leading to a more remarkable reduction in the northern area. Riparian buffers also decreased the N exports and mitigated the effects of increased urbanization (in RCP 45 + S2, RCP 45 + S3, RCP 85 + S2 and RCP 85 + S3), and the performance was better in southeast, for the reason that, the denser the stream network is, the more CWs there will be. However, different precipitation scenarios have different effects on N export, indicating that climate change may be a factor that drives the deterioration of water quality (Wilby et al., 2006). It is obvious that the influence of climate change is greater than the influence of other factors. RCP 26 + S2 and RCP 26 + S3 are exceptions to the rule that CWs are efficient tools to abate N export, demonstrating that the effects of increased precipitation in RCP26 exceed the decrease-effects of CWs.

3.5. InVEST utility and implications to N reduction

Following China's open and reform policy initiative that began in

the 1980s and the resulting population growth, urbanization and agricultural development, the JRW and Xiamen Bay have experienced substantial water degradation and eutrophication events (Hong et al., 1999; Li et al., 2011). Traditionally, phosphorus (P) is regarded as the critical element to mitigate eutrophication (Carpenter, 2008), but more importance should be given to N abatement, which could be used to control the eutrophication of river basins, estuaries and coastal seas (Smith, 2006). With the objective of enhancing sustainable development, the spatially explicit results produced by the NDR module can be used as a guide for improving watershed management and policy design. Above all, the results of the NDR module depict the area where steps should be taken to mitigate the N pollution from non-point sources. There are many measures that can be adopted, and the most essential and immediate is to decrease the amount of fertilizer use.

The findings of this study indicate that urban expansion blindly aggravates non-point source pollution and riparian CWs improve the water quality or mitigate the potential effects caused by increased urbanization and climate change. These findings prove that riparian buffers are effective approaches to intercepting and reducing the N loads entering water bodies (Mayer et al., 2007b). Even if the results are not necessarily surprising, a spatially explicit estimate of the areal increase that can be used to achieve the corresponding social benefits of improved or maintained water quality is provided. In this case, the southeast, which shows the highest areal N export rate and the relatively better N effect, should probably be prioritized for N management. Studies have been conducted to model the cost-effective solutions of N reduction in the JRW (Kong et al., 2015; Wang, 2015); thus, management that utilizes the scenarios built in this study can save an abatement cost of RMB 4 million per year at most. This will also allow for a spatial targeting of where investments to enhance N reduction are the most cost-effective, and aid in determining the tradeoffs between urban economic development and environmental protection by decision-makers. However, the results of this study also make it clear that limited N reduction effects and economic benefits are brought upon by CWs, which indicates that CWs may not be the best available green infrastructure practice in the JRW due to the intensive agriculture. Although CWs were taken as the example to explore the effect of green infrastructure on N reduction, a relatively new methodology has been proposed in this study that can be used for pollutant abatement if datasets on the loading rates and filtration rates of other contaminants (P, persistent organics, pathogens, etc.) or parameters of other types of green infrastructure practices (infiltration basin, vegetated swale, etc.) are available.

4. Conclusions

Using the NDR module of InVEST offers insight into the possible responses of freshwater ecosystem services, e.g., N reduction, in a human-dominated watershed in southeast China. Based on the results of the NDR module, the export of N from non-point sources within the JRW was 12,569 $t{\cdot}yr^{-1}$. At the county scale, the areal N load rate was relatively higher in the north of the JRW, while higher N export occurred in the southeast. The analysis of the scenarios is based on a few simple assumptions, but it considers both CWs and climate change, which is not common in the literature on ES assessments. LULC scenarios were built in this study based on the local policies and CWs. The N reduction from non-point sources in this study was mapped, and it was projected to modestly decrease under different scenarios, proving again that even though it is not the best available treatment, riparian CWs can intercept and reduce the N loads entering water bodies, especially in the southeastern area of the JRW, and these results can also inform land management decisions. However, climate change may be a factor driving the deterioration of water quality. More importantly, the methodology in this study can be generalized to address the environmental problems caused by other contaminants if the data are available and provides a tool for decision-makers to weigh the costs and benefits of urbanization and conservation.

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